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14. ABSTRACT
The planned studies include carefully conducted experimental investigations of generic types of nonlinearities likely to be encountered in aerospace structures. The experimental studies are leading to a better understanding of the physics of the underlying phenomena, thus allowing the development of suitable reduced-order mathematical models to characterize the essential features of the document structural characteristics. High-fidelity models (both parametric as well as non-parametric) are being created that have the potential to provide predictive descriptions of nonlinear system behavior under arbitrary dynamic environments.

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Progress Report on

ANALYTICAL AND EXPERIMENTAL STUDIES OF THE QUANTIFICATION AND PROPAGATION OF UNCERTAINTIES IN NONLINEAR SYSTEM MODELING AND SIMULATION

AFOSR GRANT NUMBER FA9550-04-1-0147

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ANALYTICAL AND EXPERIMENTAL STUDIES OF THE QUANTIFICATION AND PROPAGATION OF UNCERTAINTIES IN NONLINEAR SYSTEM MODELING AND SIMULATION

AFOSR GRANT NUMBER FA9550-04-1-0147

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Objectives:

The research objectives are focused on developing *methods* and *procedures* suitable for use with dynamic response measurements from flexible structural components and assemblages that may incorporate elements undergoing significant multi-dimensional nonlinear deformations. By using a powerful model-free approach to obtain computationally efficient reduced-order models, a general framework will be developed for the probabilistic representation and propagation of measured uncertainties in the stochastic nonlinear test articles, their related nonparametric nonlinear model, and the corresponding probabilistic time-history response of the physical system.

Status of Effort:

The planned studies include carefully conducted experimental investigations of generic types of nonlinearities likely to be encountered in aerospace structures. The experimental studies are leading to a better understanding of the physics of the underlying phenomena, thus allowing the development of suitable reduced-order mathematical models to characterize the essential features of the dominant structural characteristics. High-fidelity models (both parametric as well as non-parametric) are being created that have the potential to provide predictive descriptions of nonlinear system behavior under arbitrary dynamic environments.

Accomplishments:

Research activities are proceeding along two fronts: (1) an experimental phase involving the design and fabrication of an adjustable test apparatus for conducting studies on a generic multi-dimensional "joint element which incorporates important nonlinear characteristics such as non-linear elastic properties, hysteretic characteristics, and deadspace nonlinearities involving friction, and (2) an analytical phase focused on the development of a theoretical framework for processing experimental structural response measurements from uncertain systems. The objectives of these two research phases are to develop nonlinear, reduced-order, high-fidelity mathematical models, determine the response of such models under arbitrary dynamic environments, and evaluate the utility of some promising analytical tools for the quantification and propagation of uncertainties in nonlinear dynamic systems.

Experimental Studies

An innovative design was developed and implemented to construct a highly versatile two-dimensional "joint" element, which provides convenient means of generating high-quality experimental measurements that correspond to a range of nonlinear phenomena with adjustable levels of realistic nonlinearities, including hysteretic behavior, and deadspace nonlinearities incorporating Coulomb friction effects. A close-up photograph of the major elements of the multi-axis test apparatus is shown in Figure 1.

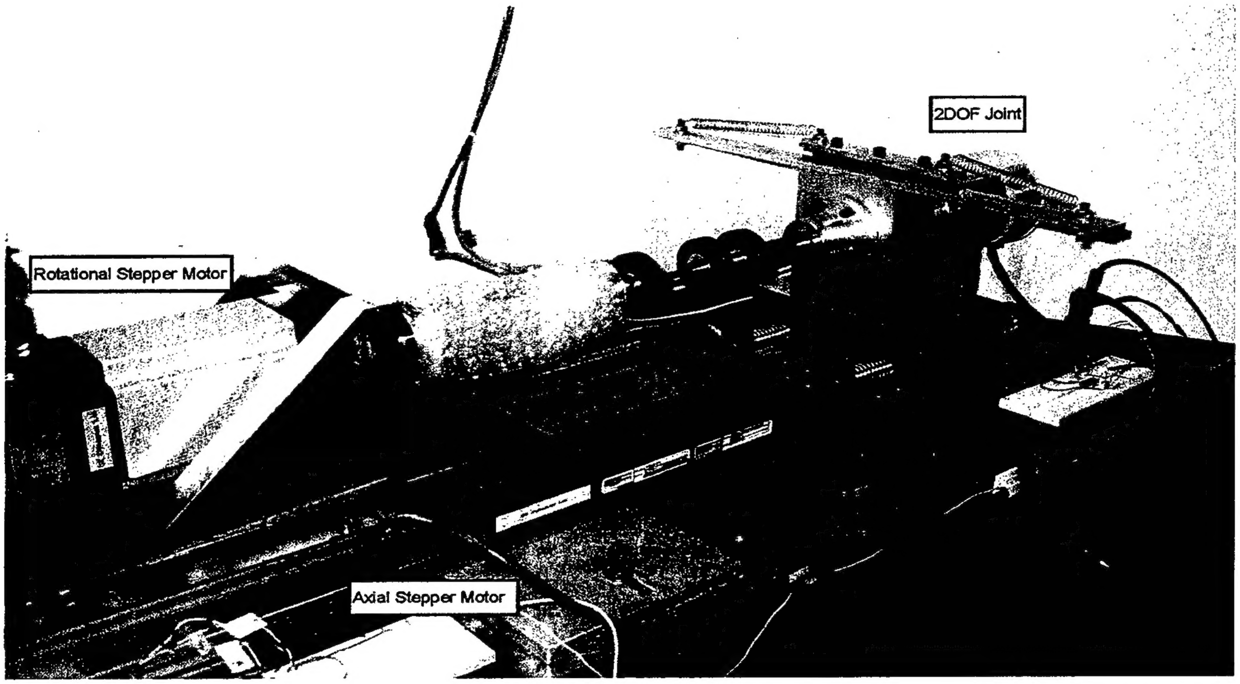

Figure 1: Close-up photograph of the instrumented two-dimensional nonlinear joint in which the nonlinear parameters in the axial as well as the rotational direction can be precisely and independently adjusted.

The experimental apparatus includes several electro-mechanical subcomponents whose function is to employ active control techniques to make the test device follow two independently controlled time-history profiles that can be arbitrarily prescribed. In order to develop appropriate physics-based simulation models, this capability is essential to populate the restoring-force surface (in hyper space) that is associated with all the joint state variables. Figure 2 shows some time-domain sample measurements of the rotational motion and force time histories, as well as a phase diagram of the force versus displacement, in which the highly nonlinear (deadspace) nature of the joint is clearly evident.

Analytical Studies:

1. *Parametric Identification of Nonlinear Systems*

As part of the effort to develop and evaluate a variety of tools and approaches for handling nonlinear multi-dimensional problems, a method previously developed by the PI and associates was used to analyze the response of the nonlinear system shown in Figure 1. The restoring force $r(x, \dot{x})$ is assumed to have hysteretic characteristics defined by the Bouc-Wen model, whose force evolution is governed by a nonlinear differential equation (Wen 1976).

2. *A General Data-Based Approach for Developing Reduced-Order Models of Nonlinear MDOF Systems*

A general procedure was developed for analyzing dynamic response measurements from complex multi-degree-of-freedom nonlinear systems incorporating arbitrary types of nonlinear elements. The analysis procedure develops a reduced-order, nonlinear model whose format is convenient for numerical simulation studies. No information about the system's mass properties is needed, and only the applied excitations and corresponding response are needed to obtain the model whose dimension is compatible with the number of available sensors. The utility of the approach was demonstrated by means of numerical simulation studies involving a three-degree-of-freedom system incorporating polynomial-type nonlinear features with hardening, as well as

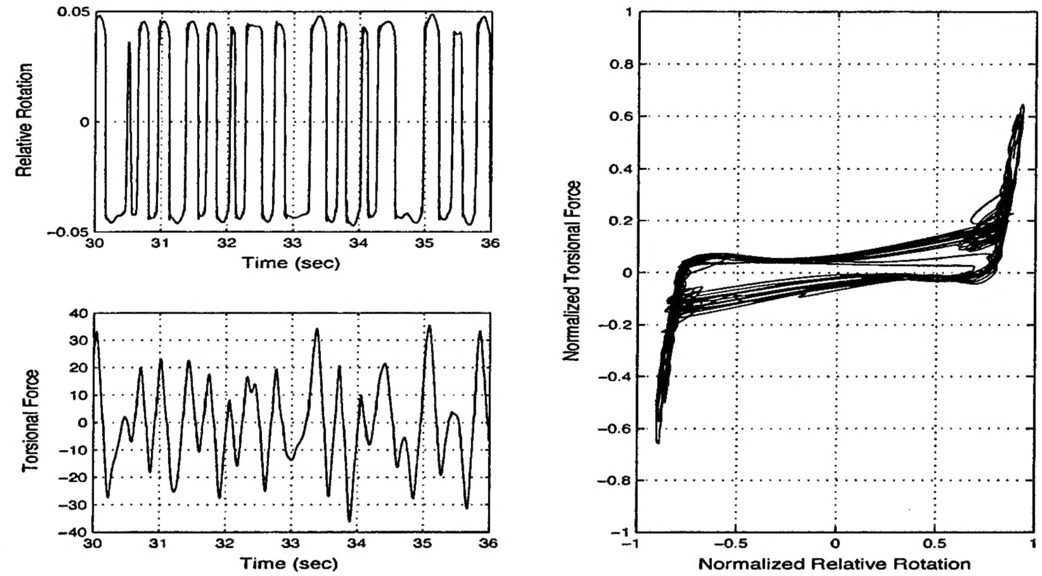

Figure 2: Response of the nonlinear joint in the rotational direction: (a) rotation time history; (b) force time history; (c) phase diagram of force versus displacement.

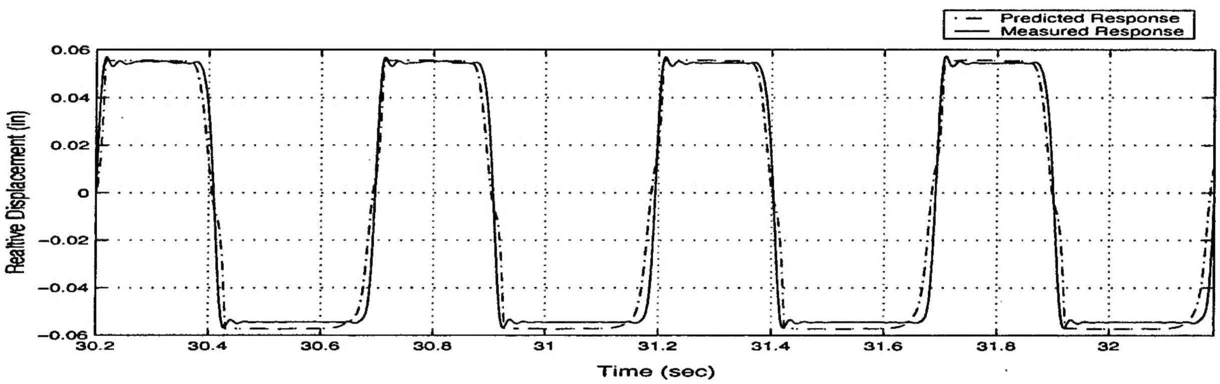

Figure 3: Identification of a Bouc-Wen hysteretic model corresponding to the nonlinear joint element.

softening characteristics.

To illustrate the application of the method under discussion, consider the example finite element model shown in Figure 4. This one-dimensional structure (rectilinear horizontal motion) consists of three masses that are interconnected by means of six truss elements anchored to an interface at three locations, thus resulting in a redundant system with three degrees of freedom. Notice that the structure of the system is not chain-like.

Consider a case where the nonlinear system under discussion is subjected to wide-band random excitation. Phase-plane plots of all the elements' force-deformation curves are shown in Figure 5, where it is clear that the elements g_1, g_5 and g_6 have a hardening–spring characteristic, while the elements g_2, g_3 and g_4 have a softening–spring characteristic. It is worth noting that while the individual element deformation characteristics are "measured" and plotted in this example, such quantities in general are not accessible for measurements, due to the non-chain nature of arbitrary systems where interaction forces between oscillating masses have simultaneous contributions from multiple (redundant) structural members. In the method under discussion, no information about the nature of element forces is utilized in the analysis. The member forces are being shown here to

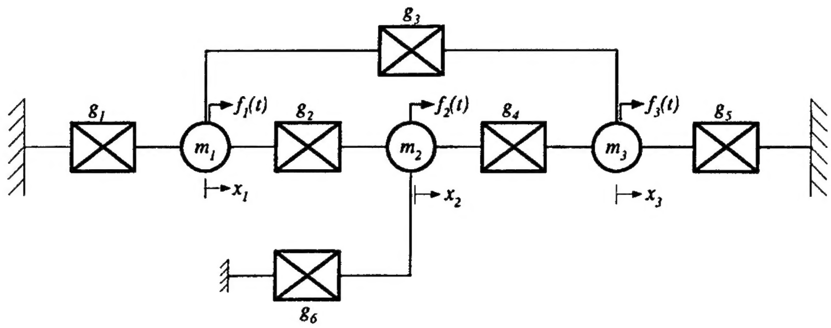

Figure 4: Model of nonlinear 3DOF system used to generate synthetic data.

demonstrate that the system is indeed undergoing significant nonlinear deformations.

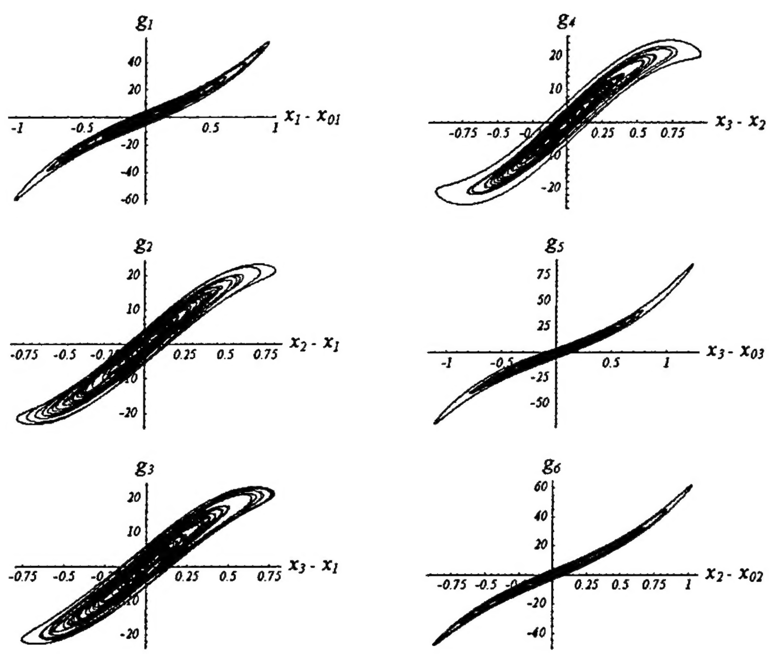

Figure 5: Phase diagram of nonlinear elements.

A graphical representation of the accuracy of the identification results is shown in Figure 6, in which the left-hand-side column of plots shows the time history of the three identified system accelerations $\hat{\ddot{x}}_1$, $\hat{\ddot{x}}_2$, and $\hat{\ddot{x}}_3$, while the RHS panel of plots corresponds to the residual accelerations r_i found by subtracting the linearized term from the "measured" signals: $r_i = \hat{\ddot{x}}_i - \ddot{x}_i$. For ease of comparison, identical time and amplitude scales are used for all the plots displayed in Figure 6.

Using standard time-marching techniques for the solution of initial-value problems, results in the predicted (estimated) system response. It was found that the exact nonlinear system response compares very well with the estimated one based on using the identified, reduced-order model.

3. *Quantification and Propagation of Uncertainties in a SDOF System*

In collaboration with the research team of Professor R Ghanem of Johns Hopkins University, a study has been initiated into the quantification and propagation of uncertainties in nonlinear dy-

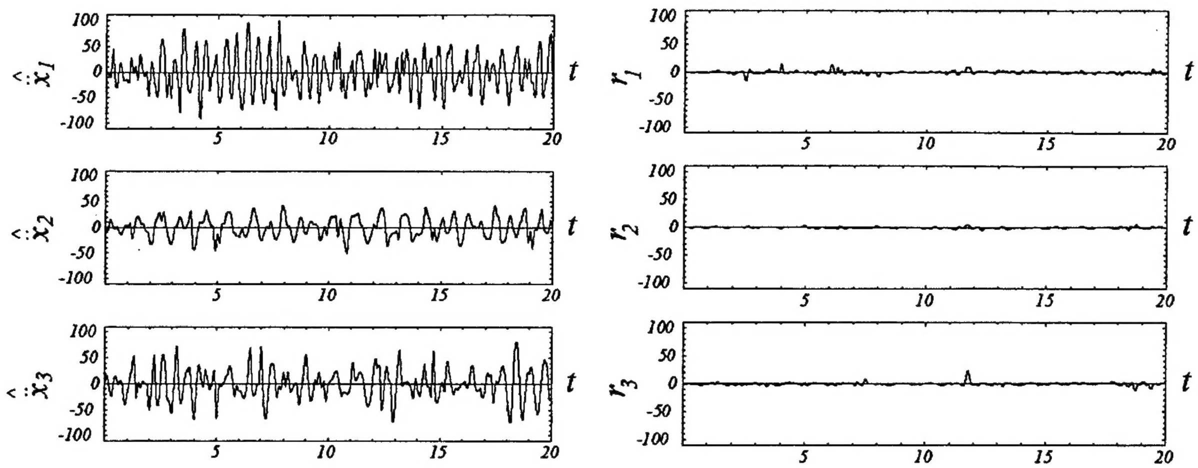

Figure 6: Comparison of estimated accelerations $\hat{\ddot{x}}_i$ and residual accelerations $r_i = \hat{\ddot{x}}_i - \ddot{x}_i$. For convenience, identical scales are used for all plotted quantities.

namic systems. In the initial phase of this study, uncertainties involving the stiffness parameter of a linear single-degree-of-freedom damped oscillator have been investigated. The stiffness term was assumed to have a Gaussian distribution and a large ensemble of response records were generated. Then by using a nonparametric system identification technique in conjunction with polynomial chaos representations (Ghanem and Spanos, 1991), the uncertainty in the identified model was determined, and represented in a form that allowed the subsequent determination of the evolving behavior of the system response uncertainties under transient loads.

Sample results from this study are presented in Figure 7, in which the upper plot shows the mean and the 2σ bounds on the displacement response, while the lower plot shows the corresponding results for the velocity response.

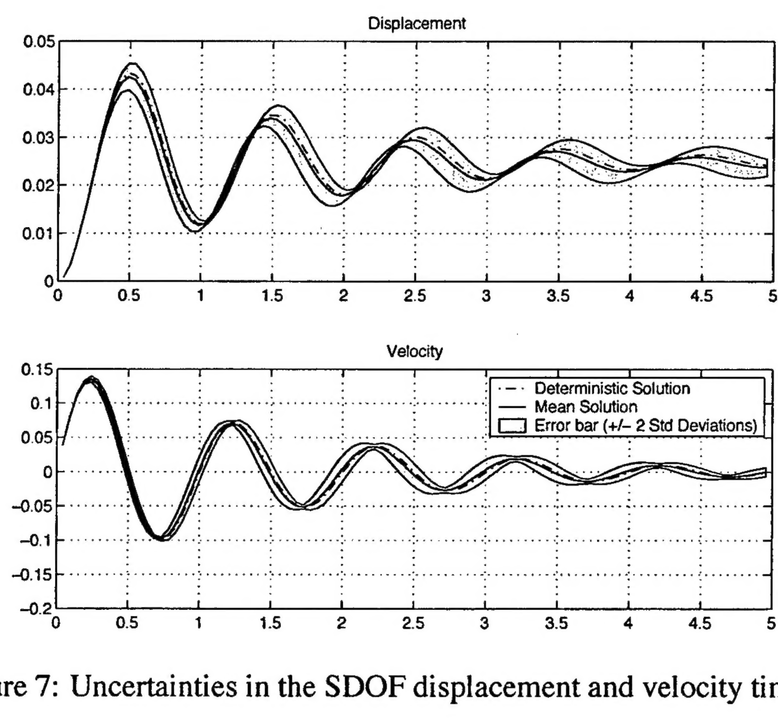

Figure 7: Uncertainties in the SDOF displacement and velocity time histories.

References

1. Ghanem, R. and Spanos, P., (1991), *Stochastic Finite Elements, A Spectral Approach*, Springer Verlag.

2. Wen, Y.K., (1976), "Method for Random Vibration of Hysteretic Systems," *J. Eng. Mech. Div. ASCE*, vol 102, (EM2), pp 249-263.

Publications:

The following papers, which are supported in part by this research effort, have been published:

1. Masri, S.F., Caffrey, J.P., Caughey, T.K., Smyth, A.W., and Chassiakos, A,G., (2004), "Identification of the State Equation in Complex Nonlinear Systems," *International Journal of Non-Linear Mechanics*, vol 39, pp 1111-1127.

2. Smyth, A.W. and Masri, S.F., (2004), "The Robustness of an Efficient Probabilistic Data-Based Tool for Simulating the Nonstationary Response of Nonlinear Systems," *International Journal of Non-Linear Mechanics,* vol 39, pp 1453-1461.

Interactions/Transitions:

Collaborative efforts are ongoing with several investigators from different institutions involving the exchange and analysis of data.

New Discoveries, Inventions, or Patent Disclosures: None

Honors/Awards: None